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Current and future power generation technologies: pathways to reducing the cost of carbon capture for coal-fueled power plants

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Abstract

As part of the United States Department of Energy's Office of Fossil Energy, the National Energy Technology Laboratory (NETL) implements research, development and demonstration (RD&D) that is focused on maximizing system efficiency and performance while minimizing the costs of coal-based power production with carbon capture and storage. In order to evaluate the benefits and market competitiveness of ongoing RD&D, NETL conducts engineering studies to evaluate the cost and performance of plants integrating multiple advanced technologies currently under development. This paper evaluates two different coal conversion pathways – combustion and gasification – and their potential to provide low-cost, low-carbon power from coal.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: combustion; gasification; coal; capture; carbon dioxide; IGCC; membrane; sorbent; turbine; fuel cell; syngas; efficiency; ultrasupercritical;

1. Introduction

The United States (U.S.) Department of Energy's (DOE) Clean Coal Research Program (CCRP) provides a worldwide leadership role in the development of advanced coal-based energy conversion technologies, with a focus on electric power generation with carbon capture and storage (CCS). As part of DOE's Office of Fossil Energy, the National Energy Technology Laboratory (NETL) implements research, development and demonstration (RD&D) in partnership with universities, other national labs and the private sector that is focused on maximizing system efficiency and performance while minimizing the costs of coal-based power production with CCS.

In order to evaluate the benefits and market competitiveness of ongoing RD&D, NETL conducts engineering studies to evaluate the cost and performance of plants integrating multiple advanced technologies currently under development. This paper evaluates two different coal conversion pathways – combustion and gasification – and their potential to meet NETL's CCRP goals.

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2. Advanced combustion systems

Today's advanced combustion systems require improvements in both cost and efficiency in order to overcome the economic penalties associated with CCS at new and retrofitted coal-fueled power plants. For combustion systems, NETL is pursuing two strategies for controlling greenhouse gas emissions: post-combustion carbon dioxide (CO_2) capture and oxy-combustion technology. For post-combustion CO_2 capture, NETL and its RD&D partners are developing advanced technologies based on solvents, membranes and solid sorbents. For oxy-combustion systems, NETL and its RD&D partners are developing advanced technologies for oxy-boilers, chemical looping systems and air separation. Furthermore, research on advanced boiler and turbine materials, back-end CO_2 purification technologies and compression of CO_2 will benefit both post-combustion CO_2 capture and oxy-combustion systems.

3. Advanced Gasification Systems

Advanced gasification systems convert coal into synthesis gas, a mixture composed primarily of carbon monoxide and hydrogen that can be used as a fuel for power generation or a feedstock in chemical production. NETL programs are developing advanced gasification technologies to meet current and anticipated environmental regulations and to facilitate the efficient pre-combustion capture of CO_2 for subsequent storage. Gasification plants are complex systems that rely on a large number of interconnected processes and technologies. Advances in the current state-of-the-art, as well as development of novel approaches, will be required to make these systems affordable and reliable for commercial deployment. Gasification systems evaluated in this analysis include Integrated Gasification Combined Cycle (IGCC) and Integrated Gasification Fuel Cell (IGFC) power plants. NETL's focus for IGCC is on the feed systems, pre-combustion CO_2 capture, syngas clean up, revolutionary oxygen supply technology, and combustion of hydrogen fuels in advanced turbines. NETL is also pursuing development of solid oxide fuel cells (SOFC) to enable high efficiency IGFC plants. The IGFC power plant is analogous to an IGCC power plant, simply replacing the gas turbine power island with the SOFC.

4. State-of-the-Art Coal Power Systems

In order to establish the benefits and advantages of advanced coal-based power systems, it is important to establish a firm basis for comparison. NETL has done this through the development of a set of cost and performance baseline power plant designs. For the systems discussed in this paper, the appropriate baseline or state-of-the-art coal power system designs, performance and cost estimates are contained in the report "Cost and Performance Baseline for Fossil Energy Power Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity." [1][2] This report establishes baselines for IGCC, supercritical (SC) pulverized coal (PC) and natural gas combined cycle (NGCC) systems both with and without CCS. Net plant efficiency and cost of electricity (COE) for the coal systems are shown in Figure 1. Compared to non-capture technology, requirements for carbon capture impose both performance and cost penalties. The penalties are primarily the result of parasitic energy and the capital cost of additional technology needed to separate CO_2 from process streams and to compress the CO_2 to a pressure suitable for pipeline transport to a storage site.

The IGCC and PC systems are modelled using Illinois #6 coal and Midwest site conditions with a plant life of 30 years and 90% carbon capture with compression to 2200 psig. Average availability and capacity factors are assumed to be 80% for IGCC and 85% for PC plants. State-of-the-art and advanced technology results presented in this paper reflect nth-of-a-kind (NOAK) cost and performance. The finance structure used for the state-of-the-art CCS systems is that associated with high-risk technologies. As plants are built and technologies are fully demonstrated, risk is expected to drop, and conventional financing associated with current PC plants would ultimately be available for NOAK advanced plants. This change in finance structure is reflected in each of the pathways as a final step, reducing the COE by approximately 2%.

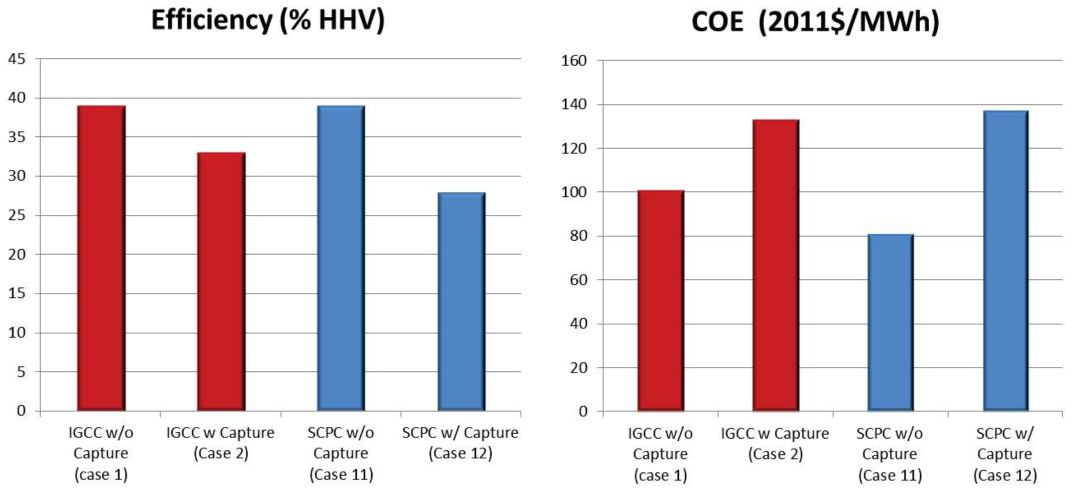

Figure 1. Cost and Performance of State-of-the-Art PC and IGCC Plants [1][2]

5. Potential of RD&D Pathways to Meet Goals

NETL has proposed CCRP goals for coal power with carbon capture. 2nd Generation technologies (research and development [R&D] complete by 2020 with initial deployments in 2025) are targeted to achieve a 20% reduction in COE compared to circa 2012 state-of-the-art technology. This corresponds to a cost of capture of approximately $40/tonne (2011 dollars) and is projected to enable coal power with CCS to be competitive with NGCC in certain regions of the U.S. when coupled with revenues for selling CO_2 for enhanced oil recovery (EOR). In the long term, Transformational R&D is needed to ensure wide-spread market competitiveness of coal with CCS in the U.S. This will require breakthrough RD&D that can provide significant reductions in COE beyond the 2nd Generation target. The achievement of 2nd Generation and Transformation RD&D goals will also increase the likelihood that CCS technology will be applied to coal-fueled power generation in international markets.

For each of the parallel pathways described above, successful RD&D from multiple advanced technologies is required in order to meet the program goals. Advanced technologies have each been assessed individually in a cumulative manner in the appropriate pathway to assess the impact to key metrics such as net plant efficiency and COE. The order in which the technologies are introduced may impact the incremental improvement provided by each advanced technology and changing that sequence could alter the relative benefits of the technologies considered. In addition, technologies evaluated are at varying technology readiness levels; thus, both the cost and performance data available to perform the evaluation and the anticipated date for commercial readiness varies significantly. Key conclusions regarding each pathway are detailed below.

6. Reducing Cost of CCS – Combustion-Based Pathways

A number of advanced technologies are applicable to both the oxy-combustion and post-combustion capture pathways, including the following:

- Advanced power cycles
- Advanced CO_2 compression systems
- CO_2 purification approaches

The advanced power cycle considered in this paper utilizes advanced ultrasupercritical (AUSC) steam conditions to improve the base plant efficiency and cost. Both pathways include transitioning from supercritical (SC) steam conditions (3500 psig/1100°F/1100°F) to AUSC steam conditions (5000 psig/1350°F/1400°F). NETL's R&D on advanced materials enables development of components to withstand the higher temperatures and pressures of the AUSC steam conditions. The cost estimates used for the boiler and steam turbine are aggressive and may require alternate boiler designs to shorten the steam leads that must be constructed using the advanced alloys. Alternative advanced power cycles are also under evaluation, such as the use of supercritical CO_2 as the working fluid in an indirect configuration. This is anticipated to provide significant efficiency benefits relative to steam power cycles, especially at higher temperatures, and would also benefit from the advanced materials R&D.

The advanced CO_2 compressor evaluated in both combustion pathways has performance and cost benefits. This compressor differs from the conventional technology in that it uses higher pressure ratios within a much smaller form factor (i.e., lower capital cost). The resulting pressurized CO_2 stream is produced at considerably elevated temperatures, allowing the process heat to be integrated elsewhere within the plant.

For both combustion pathways (and some IGFC applications), the purity requirements for the CO_2 product to meet pipeline specifications are also important in that oxygen and inerts are present in the flue gas for oxy-combustion and most non-solvent post combustion capture systems.

Removal of oxygen to low levels negatively impacts cost and performance with an estimated efficiency impact in the range of 2 percentage points. Together these points highlight a need for RD&D in CO_2 purification. A recent analysis performed by NETL aimed to optimize the CO_2 purification system used in the oxy-combustion pathway that utilized the CO_2 product as its own refrigerant, which is also known as an "auto refrigerating" system. This system essentially eliminates the external refrigeration load of the CO_2 purification system, thereby resulting in only a 0.5 percentage point net efficiency penalty compared to the 2 percentage point net efficiency penalty associated with the CO_2 purification process using external refrigeration. A simplified version of this configuration (no distillation) can also be applied in an IGCC in conjunction with advanced membrane and sorbent pre-combustion capture technologies to remove inerts (other than oxygen, which is generally not present) and recover fuel.

6.1 Post-Combustion Capture

For the post-combustion capture pathway, AUSC steam conditions provide essential base-plant efficiency and cost benefits, but the bulk of improvement is dependent on advanced post-combustion capture technologies. Evaluations of membranes and sorbents highlight a need for considerable improvement in terms of both performance and cost over first generation technologies. Membrane technologies are highly sensitive to component permeance, cost and lifetime; sorbent technologies are highly sensitive to steam usage and quality as well as the cost of the complex solids handling system including attrition. The analysis for post-combustion capture identifies performance and cost targets needed for each technology to achieve the CCRP goal of greater or equal to 20% COE reduction relative to state-of-the-art capture technology.

Two post-combustion capture (PCC) pathways are evaluated: (i) an advanced membrane-based pathway and (ii) an advanced sorbent-based pathway. Evaluation of advanced solvents systems and their capability to meet the CCRP targets by NETL and technology developers are in progress. Both of the PCC pathways begin with a reference supercritical PC plant with today's state-of-the-art carbon capture technology (i.e., amine-based solvent system) and then cumulatively add a series of technologies to the process configuration to produce electric power more efficiently and to lower the COE. The impact of each technology on both process performance and cost are evaluated.

The following advanced technologies are featured in the PCC pathway, introduced in a cumulative manner:

- Advanced CO_2 capture technology:
    - Advanced CO_2 membrane, or
    - Advanced CO_2 sorbent
- AUSC steam conditions
- Advanced CO_2 compression

Figure 2 and Figure 3 show block flow diagrams of the PC plants with capture by an advanced sorbent and advanced membrane systems, respectively.

The advanced sorbent system is fully located downstream to the plant's flue gas desulfurization unit and vents purified flue gas to the plant stack, much like a typical CO_2 solvent system configuration (Figure 2). The advanced sorbent concept itself utilizes a low heat of CO_2 adsorption sorbent that runs nearly isothermally between its capture and regeneration states. Steam is used as a sweep gas within the regenerator to cause displacement and desorption of CO_2. Within the adsorber, steam is evolved from the sorbent as CO_2 is adsorbed. Replacement of the state-of-the-art amine-based solvent CO_2 capture technology with the advanced sorbent results in a 3 percentage point (%HHV) plant efficiency gain and corresponding reduction in COE by 10%, as shown in Figure 4.

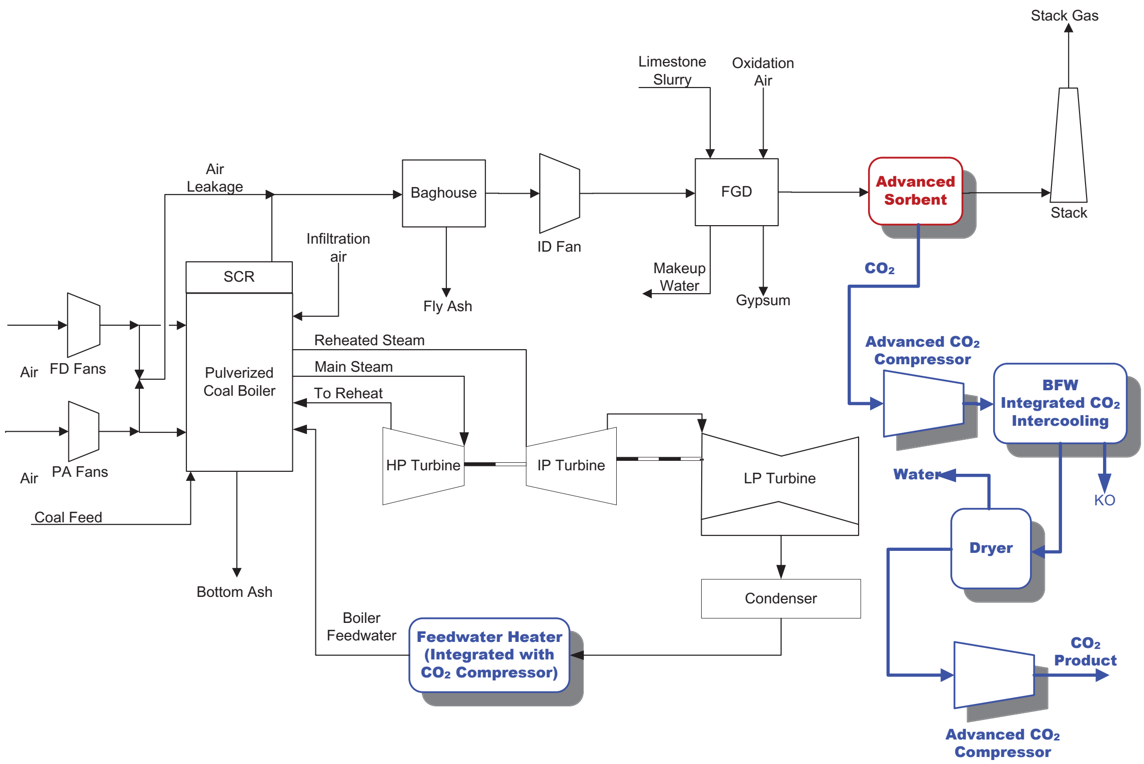

Figure 2. Advanced PC plant with sorbent post-combustion capture technology

The advanced membrane-based configuration features two membrane modules: a counter-flow membrane, and a cross-flow membrane (Figure 3). This technology differs from traditional solvent/sorbent configurations in that secondary air to the boiler is first directed through the permeate side of the counter-flow membrane module, which serves to recycle CO_2 back to the boiler, thereby increasing the concentration of CO_2 to the cross-flow membrane module and enhancing its CO_2 separation performance. Replacement of the state-of-the-art amine-based solvent CO_2 capture technology with the advanced membrane system results in a 4 percentage point plant efficiency gain and corresponding reduction in COE by 12%, as shown in Figure 4.

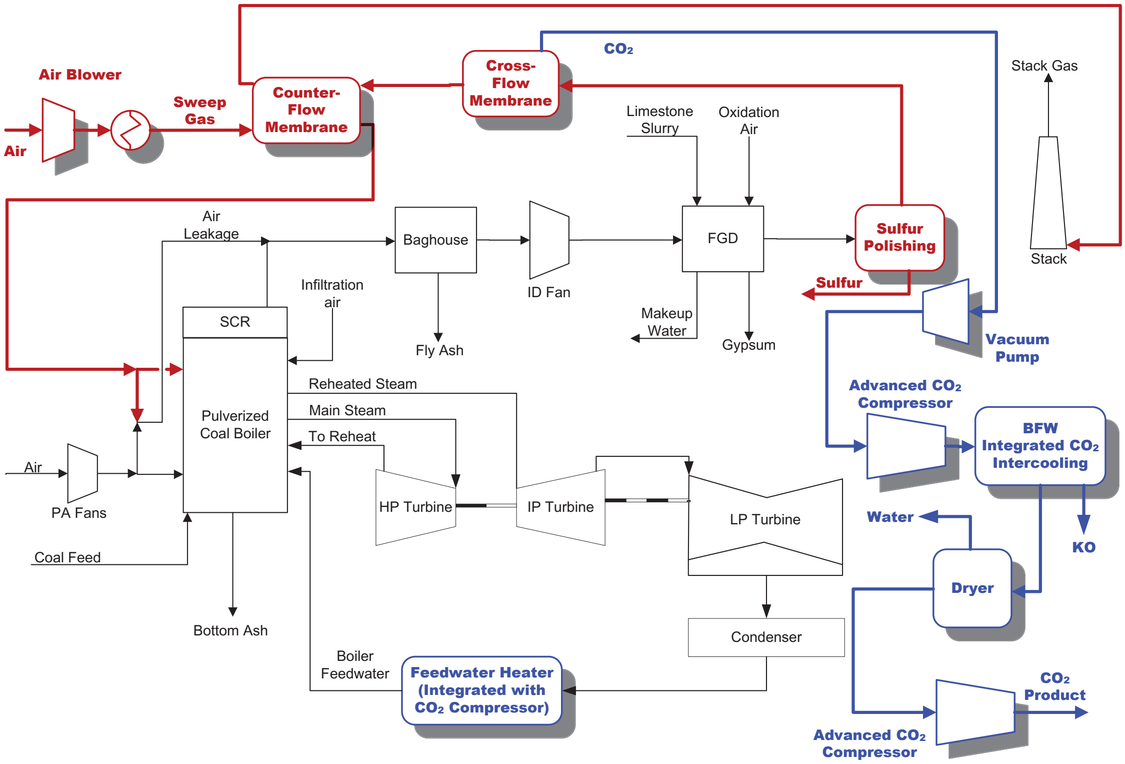

Figure 3. Advanced PC plant with membrane post-combustion capture technology

Both capture technologies as currently modeled require addition of a CO_2 purification unit (CPU) to meet required CO_2 purity and oxygen content specifications for the CO_2 product. Optimization of both the process and addition of a CPU to meet these requirements are under further investigation for the post-combustion capture pathways and, as mentioned above, can be critical to the success of these technologies.

Improvement of the steam cycle from SC to AUSC results in a 3 and 3.5 percentage point plant efficiency gain and corresponding reduction in COE by 6% and 8% for advanced membrane and advanced sorbent configurations, respectively, as shown in Figure 4. Replacement of the conventional compressors with advanced CO_2 compressors resulted in an incremental plant efficiency gain of less than 1 percentage point and corresponding reduction in COE by 1% for both pathways, as shown in Figure 4.

Considering all of the advances together and changing from a high-risk to that of a conventional financial structure yields a plant efficiency gain of 6 and 8 percentage points and corresponding reduction in COE by 21% and 23% overall, for advanced sorbent and advanced membrane configurations, respectively, relative to supercritical PC plant with CO_2 capture by a state-of-the-art amine-based solvent.

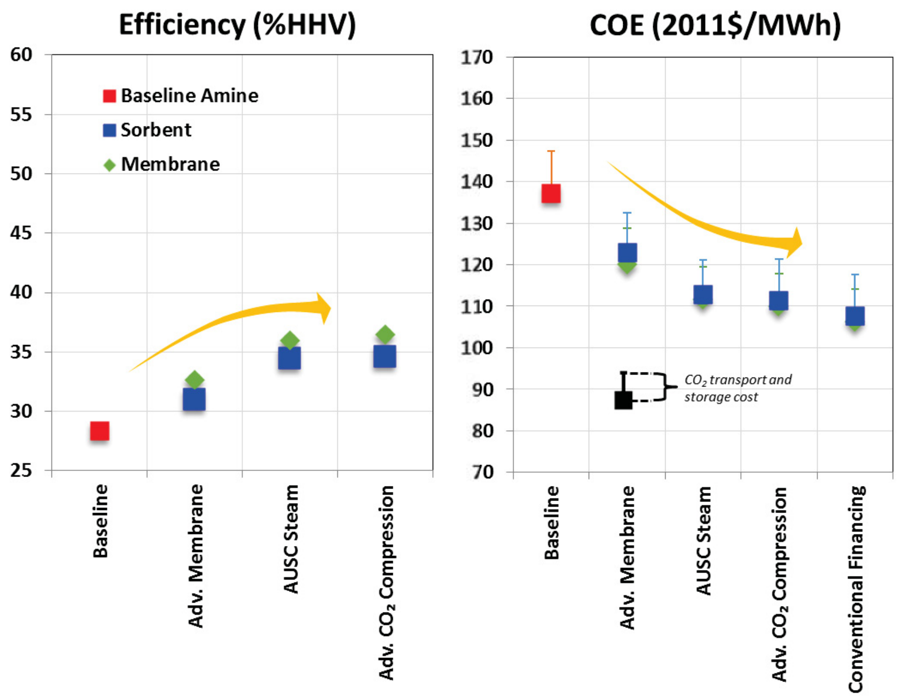

Figure 4. Cumulative impact of advanced post-combustion capture plant technology on net plant efficiency and COE[2]

5.2 Oxy-Combustion and Other Advanced Combustion Concepts

The oxy-combustion pathway is built upon a Base case where oxygen from a cryogenic air separation unit (ASU) is used as the oxidant for coal combustion in a PC plant with a supercritical steam power cycle. The CO_2-rich flue gas is cooled and sulfur is removed in a wet flue gas desulfurization (FGD) unit. The flue gas is then reheated and a portion is recycled to control the boiler temperature at approximately 2000°C (3700°F). Finally, impurities such as oxygen are removed from the flue gas in a CPU and the CO_2 product is compressed to pipeline delivery pressure. The overall 2nd Generation oxy-combustion system is found in Figure 5 which modifies the base case by incorporating the following advances:

- Advanced cryogenic ASU
- Advanced recycle
- Advanced boiler
- AUSC steam conditions
- Advanced CO_2 compressor

Additional advances in air separation using an advanced oxygen membrane and relaxation of CO_2 specifications allowing elimination of the CPU and FGD are added to the above for the Transformational case.

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[2] Data source from pending publication: NETL. (2014). Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture, Rev. 2. Morgantown, West Virginia.

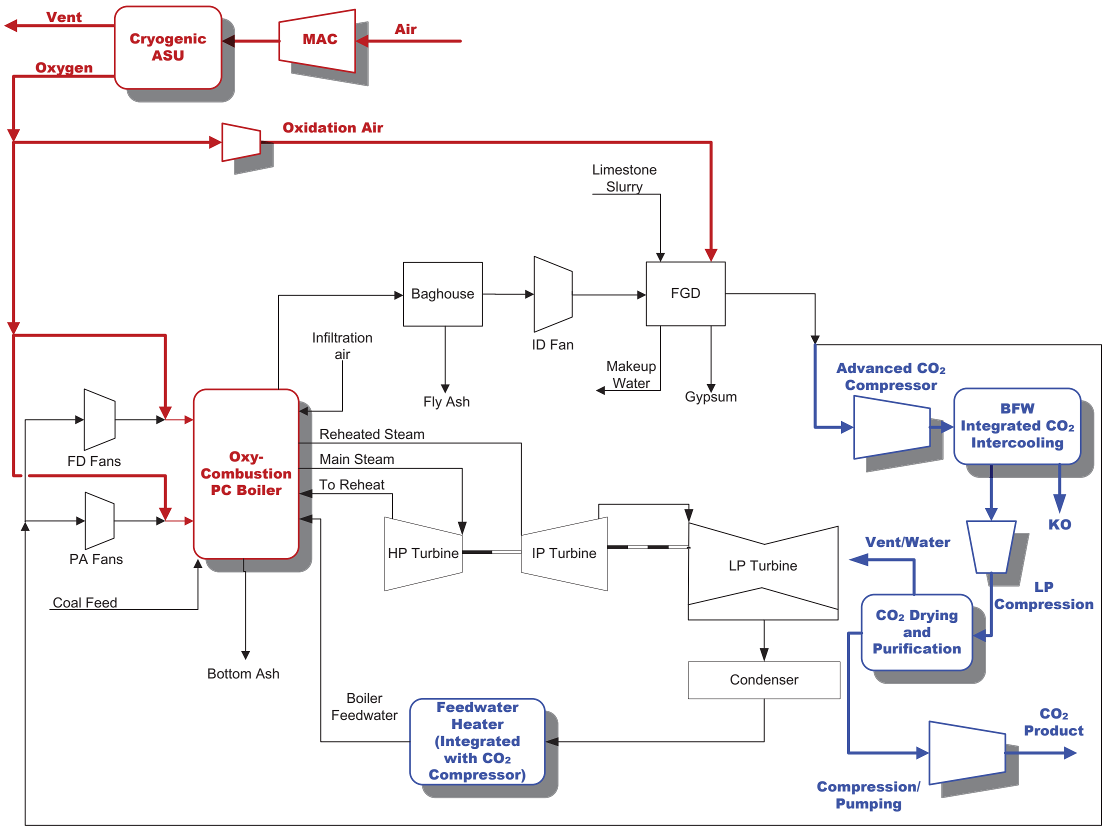

Figure 5. Advanced oxy-combustion plant

Figure 6 shows the case-by-case performance and COE results for the systems described above. The results for each case are indicative of the technology listed on the x-axis only, except for the two cumulative cases (2nd Generation and Transformational). For the 2nd Generation design, the ASU is assumed to be an Advanced Cryogenic ASU that has a similar capital cost to the state-of-the-art ASU but with a 28% reduction in power requirements. Coal is then combusted in the PC boiler using a mixture of recycled flue gas and oxygen. This is done to maintain boiler temperature profiles similar to those of air-fired conditions. The recycled flue gas is not reheated to normal air temperature, thus representing an Advanced Recycle case and eliminating the need for reheating the recycle gas. Temperatures in the Advanced Boiler case for this 2nd Generation oxy-combustion system (2,300°C or ~ 4200°F) are greater than the Base oxy-combustion case. The combustion reaction in the Advanced Boiler is used to produce steam in the same manner as most PC power plants. For this 2nd Generation system, the steam cycle modeled is at AUSC conditions.

The oxy-combustion flue gas leaving the boiler system is primarily CO_2 and water. However, other constituents that are minor in terms of concentration still need to be dealt with due to system operability or CO_2 storage and transportation requirements. An FGD is included due to the high sulfur levels present in Illinois #6 coal. This high sulfur level is exacerbated by the recycling of the flue gas. Inclusion of the FGD in the recycle loop maintains the sulfur (SO_2) concentrations at levels similar to a once through air-fired PC system. After the FGD, the process of compressing and purifying the CO_2 for storage begins. The 2nd Generation system utilizes an Advanced CO_2 compressor for the first stage of compression. After the first compression stage, the high-pressure CO_2 is cooled, and water is knocked out. At this point, the oxygen levels of the CO_2 are still too high for transportation in pipelines. A cryogenic CO_2 purification system is then utilized to remove oxygen to below 100 ppm. This is then followed by final pumping/compression to pipeline-required pressure.

Considering all of the 2nd Generation advances together and changing from a high-risk to that of a conventional financial structure yields a plant efficiency gain of ~5 percentage points relative to the Base Oxy-combustion plant and a corresponding reduction in COE by 18% overall relative to a state-of-the-art coal plant with CO_2 capture. The 20% COE reduction can be met by upgrading the CO2 purification process to the auto-refrigeration system described above.

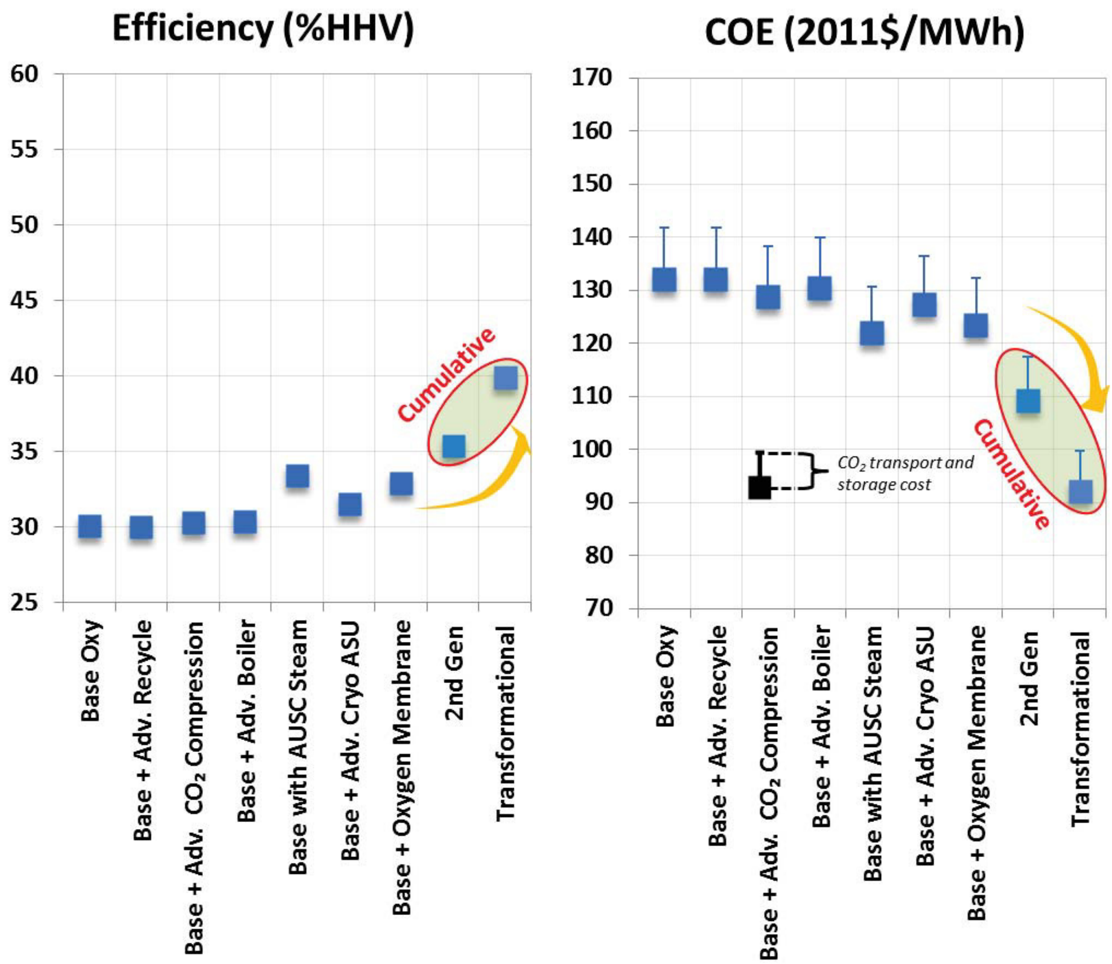

Figure 6. Impact of advanced oxy-combustion plant technology on net plant efficiency and COE[3]

Of the technologies and process changes evaluated, the largest opportunities for improving the cost and performance of oxy-combustion systems are in the ASU and the power cycle (i.e. AUSC). Figure 7 shows the breakdown of the capital cost and auxiliary load for the 2nd Generation oxy-combustion system. The figure illustrates that the ASU, even after advancements are incorporated, is a major contributor to both capital cost and auxiliary load. The capital cost of the ASU is shown to be on par with the coal boiler itself. The second chart shows that the ASU, CO_2 compression and CO_2 purification dominate the auxiliary loads. Transformational technologies, such as advanced oxygen membranes or chemical looping, which eliminates the need for a costly and energy intensive ASU, represent other key technology options.

[3] Data source from pending publication: NETL. (2014). Advanced Oxy-combustion Technology for Pulverized Bituminous Coal Power Plants. Morgantown, West Virginia.

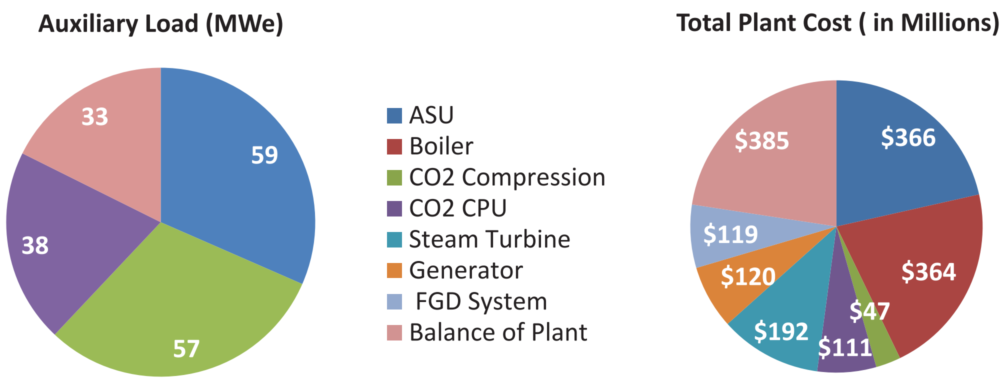

Figure 7. 2nd Generation oxy-combustion plant auxiliary load and total plant cost breakdown

To drive down the cost and energy use of the ASU, advanced oxygen membranes have been under investigation. The oxygen membrane and transformational cases highlight the potential of this technology with lower COE and higher net plant efficiencies. The transformational case in Figure 6 not only indicates the advantages of using oxygen membranes in place of a cryogenic ASU of the 2nd Generation system, but also represents the impact of modified CO_2 impurity specifications that may be achieved through on-site storage in a saline formation (no CO_2 purification unit or FGD).

Additional research and analysis is being performed on chemical looping combustion and pressurized oxy-combustion systems to evaluate their potential to drive down the capital costs of these systems and enable higher efficiency cycles capable of meeting the CCRD program goals for 2nd Generation and Transformational technologies.

7. Reducing Cost of CCS – Gasification-Based Pathways

6.1 Advanced IGCC

The IGCC pathway begins with a reference IGCC plant using conventional technology. Specifically, slurried coal is gasified using oxygen from a cryogenic ASU in an entrained flow gasifier, syngas is quenched and then shifted to convert CO to CO_2, syngas is cleaned and H_2S and CO_2 are separated in two-stage Selexol. The resulting hydrogen-rich fuel is fed to a state-of-the-art 2012 F-frame hydrogen turbine. Heat recovered from the process (e.g. radiant syngas cooler, gas turbine exhaust) is used to raise steam to power a steam turbine. The pathway then cumulatively adds a series of technologies to the process configuration to produce electric power more efficiently and to lower the COE. The impact of each technology on both process performance and cost are evaluated. In this manner, DOE can measure and prioritize the contribution of its R&D program to future power systems technology with regards to IGCC.

The IGCC technology pathway builds upon the reference IGCC technology by incorporating the following advanced technologies in a cumulative manner:

- Advanced hydrogen turbine (AHT)
- Ion transport membrane (ITM) for oxygen production
- Warm gas clean up (WGCU)
- Hydrogen membrane for pre-combustion capture

Figure 8 shows a block flow diagram of the advanced IGCC integrating all of the above advanced technologies.

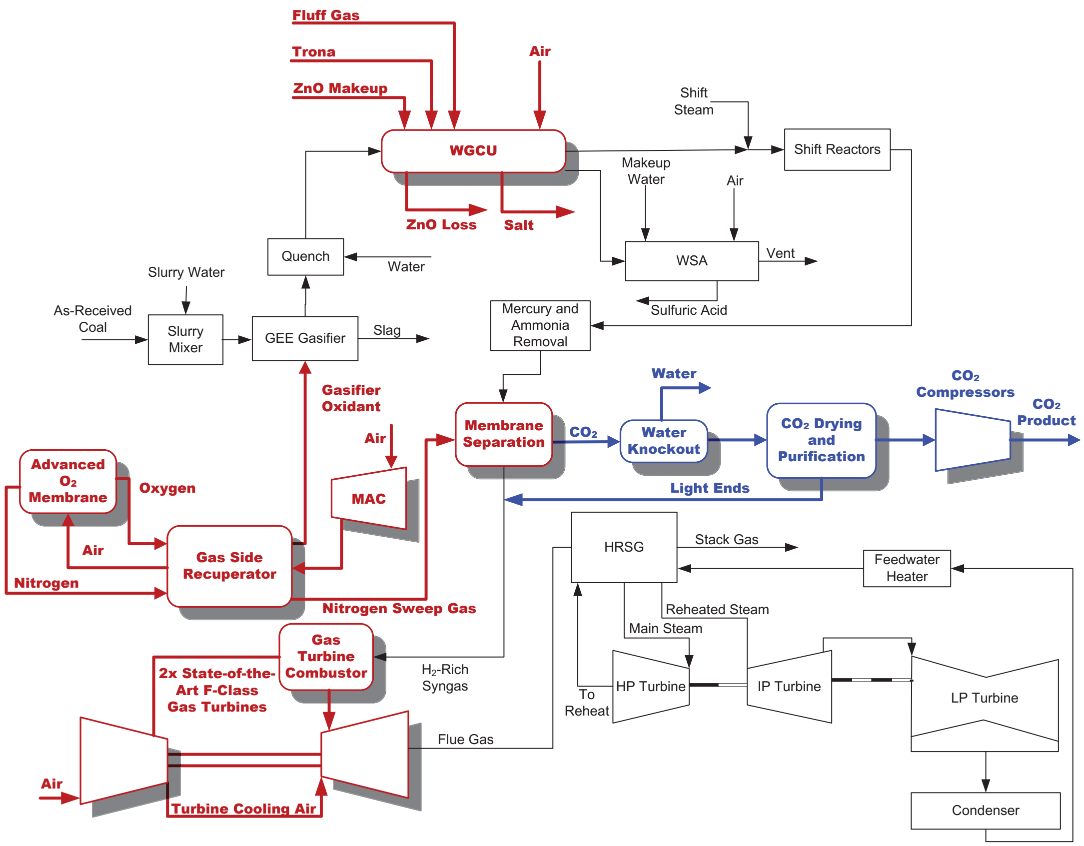

Figure 8. Advanced IGCC plant

The AHT is critical to the success of this pathway due to the increase in efficiency and reduction in capital costs per net power output. Additional performance and cost reductions are projected to be achieved using the ITM, WGCU and advanced pre-combustion capture technologies. Assuming R&D success in terms of performance and cost and successful integration of these technologies, these advanced technologies provide a pathway to an advanced IGCC plant with 90% carbon capture that is 7.0 percentage points greater in efficiency and reduces the COE by 28% relative to the state-of-the-art carbon capture IGCC plant. The increase in efficiency and decrease in COE are shown in Figure 9.

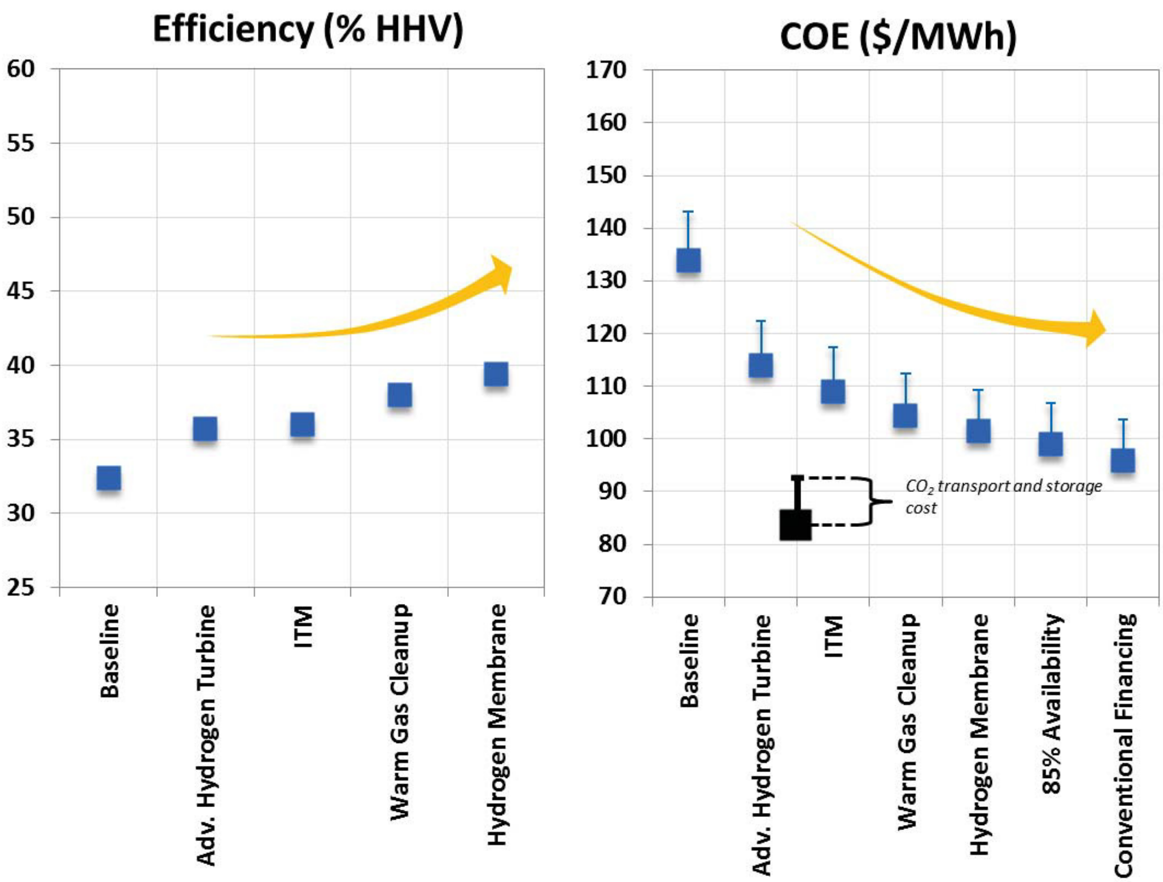

Figure 9. Cumulative impact of advanced IGCC technology on net plant efficiency and COE[4]

The first technology added to the process is the AHT, which replaces the state-of-the-art F-class turbine. The higher firing temperature (~2650°F) afforded by the AHT not only improves the process efficiency, but also results in ~45% increase in gas turbine output, resulting in a significant increase in the plant net power and flow rates such as coal input. Economies of scale associated with this size increase provide additional cost reductions. Upgrading the turbine decreases COE 14.5% and increases process efficiency by 3 percentage points, the largest gains for any equipment investigated in this study.

The second technology implemented is an ITM, which replaces the cryogenic ASU previously used. An ITM is a ceramic-based membrane that only allows oxygen to permeate at operating temperatures between 800–900 °C. The ITM provides oxygen for the gasifier and the Clause plant, while the nitrogen stream is used as a hydrogen diluent to the topping combustor in the turbine. The ITM provides more energy efficient separation than the ASU, but the auxiliary duty for compression of the inlet air and low-pressure oxygen results in net power consumption similar to the ASU. The significant advantage of the ITM is that the targeted cost is approximately two-thirds of the ASU, which significantly reduces the capital costs and results in a 3% reduction in COE. This configuration does not include air-side integration with the turbine which is anticipated to increase the efficiency and COE benefits of the ITM.

Replacing conventional gas cleaning technologies with a WGCU process train allows for the syngas to be cleaned without the associated

[4] Data source from pending publication: NETL. (2014). Current and Future IGCC Technologies Volume 2: A Pathway Study Focused on Carbon Capture Advanced Power Systems R&D Using Bituminous Coal, Revision 2. Morgantown, West Virginia.

decrease in efficiency from cooling and reheating the fuel gas stream. The WGCU process train consists of 1) chloride removal; 2) carbonyl sulfide and hydrogen sulfide removal in a high-temperature desulfurization system with sorbent regeneration; 3) sulfur recovery from the wet sulfuric acid process; and 4) novel high-temperature trace contaminant removal system to remove ammonia and mercury. This system replaces one of the Selexol stages associated with the desulfurization, mercury removal process, water-gas shift reactor and Claus plant, and performs all of these operations at elevated temperatures. Implementing the WGCU process train results in a 2 percentage point increase in net plant efficiency, which is mostly the result of increased power generation from the steam turbine via increased heat recovery from the process. A 4% decrease in COE is also realized.

The final technology to be implemented is a palladium-based 100% hydrogen-selective membrane that replaces the single stage Selexol for CO_2 capture from the syngas. The nitrogen previously used to dilute the hydrogen prior to entering the turbine can be used as sweep gas on the permeate side of the membrane to maintain a low partial pressure of the hydrogen. The resulting retentate consists mostly of pressurized and hydrated CO_2, which can be dehydrated via cooling for carbon storage or reuse. Use of the palladium membrane improves plant efficiency by 1.4 percentage points mostly from the lower compression costs of CO_2. The COE is further reduced by 3%, again mostly due to lower compression costs. Additional analysis is underway of alternative advanced pre-combustion technologies such as low cost polymer-based membranes and solid sorbents. Many of these alternatives also benefit from pairing with WGCU and production of CO_2 at elevated pressure with an added benefit of humidification of the syngas.

General advances in IGCC plant operation are also included in the pathway study in the form of improved plant availability and increased capacity factor, which are assumed to be possible through advanced component monitoring, improved maintenance practices, and plant operation experience. For this analysis, capacity factor and availability are equivalent. Increasing the availability from the baseline of 80% to 85% will lower the COE because of increased power generation for the same capital and fixed operation and maintenance (O&M) costs. The result is a further reduction of 3% in COE.

Implementation of all these technologies allows for an estimated increase of 22 percentage points for efficiency, which is shown in Figure 9. Coupled with increased availability and improved financing structure, a reduction of 28% in COE has also been estimated and is shown in Figure 9. The AHT was the largest contributor to both the efficiency increase of 14.5 percentage points and the reduction in COE of 3%.

6.2 Advanced IGFC

IGFC systems represent a transformational technology pathway that provides high efficiency and renders low capture costs for CCS. The IGFC power plant is analogous to an IGCC power plant by simply replacing the gas turbine power island with a SOFC island. SOFCs provide for high efficiencies associated with the nearly reversible electrochemical conversion of coal-derived synthesis gas (syngas) chemical potential to electric power. The SOFC simultaneously provides oxygen separation and, thus, requires only a small oxy-combustor or separation process to remove unconverted fuel in order to produce a high purity CO_2 stream. The heat produced by the SOFC system can be recovered further in a combination of Brayton and Rankine thermodynamic cycles, depending on the SOFC operating pressure.

SOFCs have the ability to produce electrical power with a variety of fuels in addition to syngas, including natural gas. IGFC performance and cost improves significantly with a higher methane (CH_4) content syngas fuel. This fuel flexibility leads to the possibility of using multiple fuels, earlier demonstration on natural gas systems, and potential application in a distributed generation system.

The IGFC technology pathway builds upon the reference IGFC technology by incorporating the following SOFC improvements and advanced technologies in a cumulative manner:

- Reduction of SOFC stack performance degradation
- Reduction of SOFC stack overpotential at normal operating conditions
- Enhancement of conventional gasifier
- Reduction of SOFC stack cost
- Improvement of inverter efficiency
- Replacement of conventional gasifier with a catalytic gasifier

Figure 10 shows a block flow diagram of the advanced IGFC integrating all of the above advanced technologies. **Error! Reference source not found.** summarizes the conditions and technologies evaluated along the pathway.

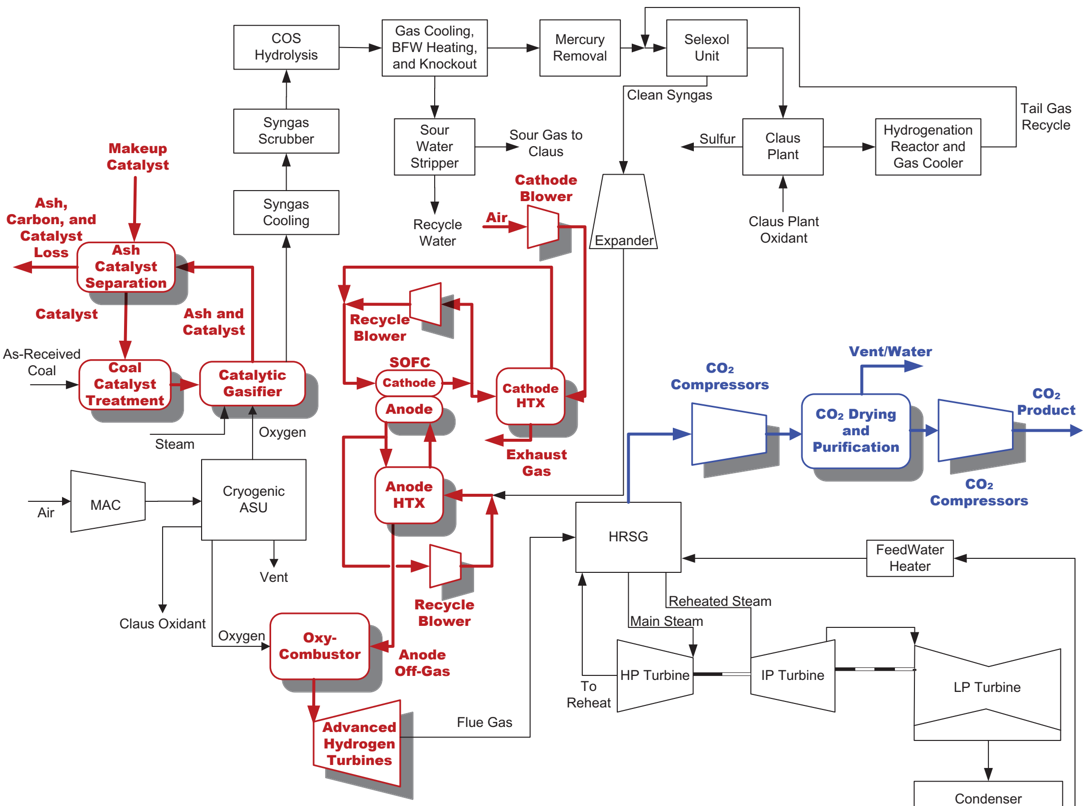

Figure 10. Advanced IGFC plant

<table>
<tr><th>Pathway Parameter</th><th>Reference IGFC</th><th>Degradation</th><th>Overpotential</th><th>85% Availability</th><th>Enhanced Gasifier</th><th>90% Availability</th><th>SOFC Cost</th><th>Inverter Efficiency</th><th>Catalytic Gasifier</th></tr>
<tr><td>SOFC Degradation Rate [%/1000 h]</td><td>1.5</td><td colspan="8">0.2</td></tr>
<tr><td>SOFC Overpotential [mV]</td><td colspan="2">140</td><td colspan="7">70</td></tr>
<tr><td>Availability [%]</td><td colspan="3">80</td><td colspan="2">85</td><td colspan="4">90</td></tr>
<tr><td>Dry Syngas CH_4 Content [%]</td><td colspan="4">5.8</td><td colspan="4">10.8</td><td>32</td></tr>
<tr><td>SOFC Stack Cost [$/kW][1]</td><td colspan="6">225</td><td colspan="3">200</td></tr>
<tr><td>Inverter Efficiency [%]</td><td colspan="7">97</td><td colspan="2">98</td></tr>
</table>

1 – Cost of the SOFC stack unit (stacks, enclosures, inverters) in $ per kW of AC output
2 – NETL's goal for SOFC stack cost is $225/kW

Figure 11. Summary of IGFC pathway conditions

SOFC improvements have the potential to significantly increase the efficiency of IGFC plants over the baseline technology. SOFCs are susceptible to performance degradation over time with state-of-the-art performance degradation of approximately 1.5% per 1000 hours. NETL's goal for performance degradation is 0.2% per 1000 hours, which will allow the SOFC to operate for over 40,000 hours, decreasing costs associated with SOFC replacement over the plant lifetime and significantly decreasing the COE of the plant as shown in **Error! Reference source not found.**. Improvements to allow operation at a lower overpotential result in an efficiency improvement and cost reduction. Additional incremental improvements in efficiency (up to 4 percentage points) can be realized by operating the SOFC at an elevated pressure (not presented in this paper).

Improvements in gasification technology have the potential to increase the methane content in the syngas, which is beneficial to the SOFC operation because it reduces the amount of air flow needed for SOFC stack temperature control by providing local cooling of the SOFC stack through the endothermic methane reforming reaction. Incorporation of the enhanced gasifier results in nearly doubling the methane content to over 10% (dry). Introduction of catalytic gasification increases the methane content to over 30% (dry) and also minimizes the consumption of oxygen by operating at a lower temperature, giving better efficiencies than gasification at higher temperatures. Direct addition of natural gas to the syngas stream is an alternative to the catalytic gasifier. This reduces the dependence of the IGFC pathway on catalytic gasifier development but results in a system whose COE is linked to natural gas prices.

General advances in IGFC plant operation are also included in the pathway study in the form of improved plant availability and increased capacity factor, which are assumed to be achieved through advanced component monitoring, improved maintenance practices and plant operation experience. For this analysis, capacity factor and availability are equivalent.

As shown in Figure 12, net plant efficiency for the IGFC pathway (including CCS) increases from the reference value of 39.5 to 54 percent, resulting in the highest efficiency pathway. Figure 12 also shows the corresponding decrease in the COE for the IGFC pathway. The base value of $170/MWh is improved to $84/MWh (with CO_2 transport and storage [T&S] costs). The IGFC meets NETL's 2nd Generation goal of 20% COE reduction compared to state-of-the-art IGCC with CCS when SOFC degradation and overpotential R&D targets are met and availability improves to 85%. All other advances support NETL's transformational goal, significantly exceeding 20% COE reduction.

When considering the higher power conversion efficiencies of IGFC plants compared to conventional fossil fuel power plants, and CO_2 removal efficiencies that are greater than 98% (compared to 90% used as a design basis for conventional fossil fuel power plants), IGFC plant emissions of CO_2 are lower than those in conventional fossil fuel power plants with CCS by a factor of 4 to 10. In addition, with the transformational improvements, the proposed Environmental Protection Agency (EPA) target of 1100 lb/MWh$_{GROSS}$ can be met in an IGFC even without CCS. In addition, due to only a small steam cycle and its associated cooling water need, water demand for IGFC is significantly below that of other coal plants with CCS.

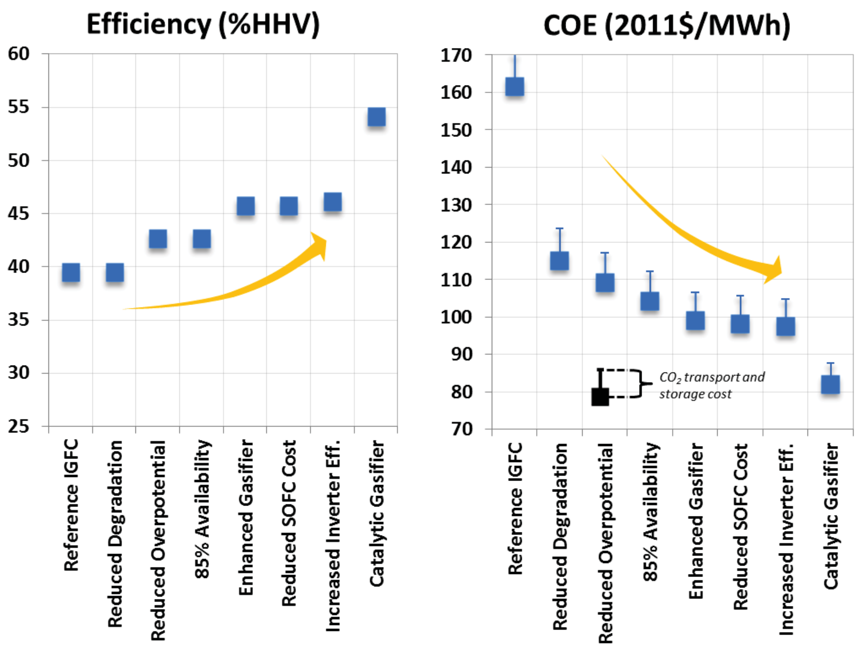

Figure 12. Cumulative impact of advanced IGFC technology on net plant efficiency and COE[5]

8. Conclusion

Advanced technologies have each been assessed individually and cumulatively in the appropriate combustion and gasification pathways to assess the impact to key metrics such as net plant efficiency and COE. Technologies evaluated are at varying technology readiness levels; thus, both the cost and performance data available to perform the evaluation and the anticipated date for commercial readiness varies significantly. For each of the parallel pathways described above, successful RD&D from multiple advanced technologies is required in order to meet the program goals. Key conclusions include:

- Technologies providing improvement in power cycle efficiency (AHT, SOFC, AUSC steam conditions) are key to each pathway through reduction of fuel prices and by spreading significant capital costs for coal CCS plants over greater net power.
- Reduction of auxiliary loads and cost improvements of supporting systems, such as oxygen production and gas cleanup, are critical to advanced oxy-combustion and IGCC.
- Improvements in the energy penalty and cost associated with CO_2 capture technology play a significant role in the post-combustion capture pathway and are applicable to both greenfield and retrofit applications.

Analysis of the various combustion and gasification systems highlights how successful RD&D can provide parallel pathways to significantly improve the efficiency and decrease the COE of coal plants with CCS and, ultimately, meet DOE/FE objectives to provide low-cost, low-carbon power from coal.

[5] Data source from pending publication: NETL. (2014). Techno-Economic Analysis of Integrated Fuel Cell Systems. Morgantown, West Virginia.

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